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INVESTIGATION OF S-IV ALL SYSTEMS VEHICLE EXPLOSION

Compiled and edited by J. B. Gayle

George C. Marshall Space Flight Center

Huntsville, Ala.

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INVESTIGATION OF S-IV ALL SYSTEMS VEHICLE EXPLOSION

SUMMARY

Investigation of the S-IV All Systems Vehicle explosion indicated the following: high explosive equivalent, 1 percent; fireball diameter, 380 feet; fireball duration, 11 seconds; maximum fragment radius, 1500 feet. The relatively low yield was due to substantially instantaneous ignition of the spilled propellants which probably resulted from the extreme flammability of hydrogen. If this trend persists in the scale model test programs now in progress, some reduction in the 60 percent high explosive equivalent currently used for siting of LOX/LH_2 vehicles may be possible.

INTRODUCTION

On January 24, 1964, the S-IV All Systems Vehicle exploded and burned during the terminal stages of the countdown for its initial test firing. The incident which occurred at Test Stand 1 of the Douglas Aircraft Company (DAC), Sacramento test facility was the second known failure involving significant quantities of the propellant combination, LOX/LH_2. REF. 1 Inasmuch as the previous failure involving these propellants occurred during the booster phase of the first Centaur launch, the S-IV All Systems Vehicle explosion was the first for which a detailed examination of the resulting damage was possible.

A number of small scale studies currently are being conducted to assess the hazards associated with the use of LOX/LH_2 and other propellant combinations; however, extrapolation of the results of these studies to obtain siting criteria introduces a considerable degree of uncertainty which can best be eliminated or minimized by tests involving full-scale tankage of flight weight construction. Although such tests are contemplated, they are not expected to be accomplished before FY-66. Therefore, it was considered mandatory that a comprehensive investigation be made of the S-IV All Systems Vehicle explosion and that the information be analyzed with respect to the currently accepted siting criteria for LOX/LH_2. 15

THE COMMITTEE

The chairman of the investigating committee was Dr. W. R. Lucas, Chief of the Materials Division, Propulsion and Vehicle Engineering Laboratory, Marshall Space Flight Center (MSFC). The alternate chairman was Dr. J. B. Gayle, Chief of the Physical Chemistry Section, Chemistry Branch, Materials Division, MSFC. Other members from MSFC were: Mr. H. C. Dyer, Test Laboratory; Mr. L. L. Roberts, Safety Office; and Mr. O. S. Tyson, MSFC resident engineer at DAC Sacramento. Members from other NASA organizations were: Dr. F. E. Belles, Lewis Research Center; Mr. P. V. King, Cape Kennedy; and Mr. G. D. McCauley, NASA Headquarters. Members from Air Force installations were: Mr. C. R. Cooke, Edwards Air Force Base, and Mr. L. J. Ullian, Patrick Air Force Base. Dr. P. A. Longwell, California Institute of Technology, served as a member representing DAC. Consultants to the committee were Mr. A. J. Hoffman, Ballistic Research Laboratories (BRL), and Mr. W. M. Smalley, Aerospace Corporation.

MODE OF INVESTIGATION

The committee met at 9:00 a.m. at DAC, Sacramento on February 5, 1964. Dr. Lucas was unable to attend because of a longstanding previous commitment so the alternate chairman, Dr. Gayle, presided. He stated that the purpose of the committee was to investigate the nature and magnitude of the explosion, insofar as possible, from a post-mortem examination, but was not to consider the cause of the failure except as it related to the magnitude of the explosion.

Information prepared in advance was distributed. This included air and ground-based photographs of the test stand and maps of the area showing fragment dispersion and glass breakage. A briefing on the events leading to the explosion and the then-current theories regarding the probable cause of the explosion were given by Mr. Ted Gordon, Chief Engineer, DAC, Sacramento. Four color films of the explosion were shown: one from each of the upstream and downstream cameras located roughly 300 feet from the stand, and one from each of two engine area cameras located approximately 10 feet from the vehicle on the level just below that at which the explosion appeared to occur. After detailed inspection of these films, the group visited the explosion site for a quick look and then reconvened for initial discussions. Because it was evident that a systematic examination was essential, the committee was divided into three groups. One group was responsible for surveying the entire area to obtain detailed information on fragment dispersion. A second group was responsible for noting the damage suffered by small, nearby structures such as Butler buildings and trailers. This group also examined several damaged beams located on the test stand in the immediate vicinity of the explosion. The last group examined the test stand in as much detail as time permitted.

After completion of these assignments, the committee reassembled for further discussion. Because it appeared impractical to attempt an on-the-spot assessment of the findings, specific items of data were assigned to various individuals for consideration and evaluation following the meeting. After receiving these assignments, most of these individuals spent the second day of the meeting obtaining additional photographs, measurements, and other pertinent information on their assigned portions of the investigation. Arrangements were made to obtain similar data for LOX/RP-1 explosions for comparison, and liaison with the committee investigating the cause of the explosion was established. The test stand then was released to Mr. O. S. Tyson, and the meeting was adjourned.

FINDINGS

Weights and conditions of on-board propellants and pressurization gases at the time of the explosion are given in Table I. The indicated weights of LOX and LH_2 were, respectively, 84,244 and 16,954 pounds for a combined propellant weight of 101,198 pounds.

A detailed discussion of the events preceding the explosion and the probable underlying causes of the incident are contained in the classified report of the committee responsible for investigating this aspect of the incident (Ref. 1). The immediate cause of the failure was the overpressurization of the LOX container. Extrapolation of test records indicated that failure occurred at a LOX pressure of approximately 100 psia or well above the design limit for the vehicle. Frame-by-frame inspection of the various films suggested that initial rupture occurred around the periphery of the common bulkhead and that ignition occurred immediately upon rupture. Thus, there was no visual or other evidence to indicate spillage of the LOX before ignition. This could indicate that rupture of the external skin of the LOX tank was followed by similar rupture of the LH_2 tank within a few milliseconds. Another failure mode which cannot be excluded is the initial rupture of the common bulkhead, probably with simultaneous ignition of the propellants, and subsequent rupture of the external skin of the vehicle. Still other modes are possible; however, regardless of the actual mode of failure, all available evidence indicates that there was little or no time for mixing of the propellants before ignition. Inspection of the films suggested that the explosion originated near the center line of the test stand and near the deck of level No. 5. Inspection of damage to the test stand indicated that the center of the explosion could be approximately located at a point, in the vertical direction, midway between the juncture of the common bulkhead and the side wall and the uppermost portion of the curved bulkhead.

It also appeared to be five feet to the west of the vertical center line of the tank. Thus, the apparent center of detonation was at a height of 55 feet above the hard surfaced apron on which the stand was located and five feet west of the north-south center line.

Inspection of photographs prepared by enlarging individual frames from one of the engine area cameras indicated that the initial motion of the vehicle caused by the explosion had a definite westerly vector. This was determined by locating readily definable parts of the vehicle with reference to the test stand structure from photographs taken immediately before and after the start of the explosion. The results are shown in FIG 1. The movement from left to right shown in this figure represents movement in a north-west direction. Since this analysis indicates that the initial movement of the upper part of the vehicle was toward rather than away from the apparent center of the explosion, it appears that the principal explosion may have been preceded by a smaller one located near the periphery of the vehicle.

The area surrounding the test stand was roped off immediately after the explosion, and access was rigidly controlled thereafter. This greatly facilitated the work of the committee and, in particular, insured the validity of surveys of shrapnel dispersion and test stand damage.

Figure 2 shows the test stand and vicinity after the explosion. Inspection of this figure indicates that the overhead crane and supporting structures were virtually undamaged and that the effects of the explosion were largely confined to the test stand proper.

Figure 3 is a map showing the location of debris which was dispersed as shrapnel. Table II gives the identification of the fragments shown on FIG 3. Table III is a tabulation of the approximate sizes, weights, and locations (in distance from the center of the explosion) of fragments selected for possible detailed investigation.

Glass breakage occurred at distances up to approximately 1,100 feet from the center of the explosion, as shown in FIG 4. Most significant to this study were windows broken in guard shacks, house trailers, and Butler buildings.

The Butler Building designated TS-1 suffered what we considered relatively light damage (FIG 5). One end of this building was positioned facing the blast, with the nearest surface at a distance of 210 feet from a point on the ground directly below the assumed center of the explosion. Damage to the test stand is described by individual levels.

Basement Level

The doors of the basement switch and generator room were blown inward and were off their hinges. These were metal doors, each 4 ft. 2 in. by 8 ft. 6 in. However, no damage was done inside the room.

Level No. 1

The elevator car experienced some deformation of the roof downward, and one sheet metal panel of the roof was peeled upward. There had been a small fire in the elevator. The double metal doors (4-1/2" by 8'6") of the terminal room were blown inward, one being blown off its hinges. A cabinet was hit by the door, and this, in turn, jammed a desk. Otherwise, there was no apparent damage in the terminal room.

The galvanized iron roof over the stair landing between levels 1 and 2 was deformed, and part was blown-off.

Level No. 2 (Firing Level)

Much debris had fallen from above, but there was little damage to the stand at this level. There had been some fire because flammable items were singed. It appeared that droplets of liquid oxygen had sprayed the area since paint on the steel was charred in a droplet pattern. However, the steel had not been heated appreciably.

Some exposed wiring at the south end of the level was badly charred. Liquid oxygen had apparently flowed over the south concrete deck.

Level No. 3

There was relatively little debris at this level. Exposed wiring was charred in many instances, and electrical power cables in the vertical cable duct had charred insulation. A lightweight sheet metal air duct was smashed. The structure, however, was essentially undamaged. Paint was charred in a droplet pattern, presumably because of liquid oxygen spray, but the metal had not been heated appreciably.

The liquid oxygen sled did not appear damaged. On the liquid hydrogen sled, flammable foam insulation was burned and valve handles were singed, but damage appeared inconsequential (FIG 6).

Level No. 4

The cableways, made of lightweight metal, were torn loose and distorted; exposed wires were charred. The power cables in the vertical cable duct were charred. A few light fixtures were knocked off their conduits. There were fire marks on painted steel, apparently due to liquid oxygen droplets, but the steel had not been heated significantly; there did not appear to be significant structural damage.

The liquid oxygen flexible fill line was burned through at a point west of the vehicle location and overhead. This line was partly protected by structure and piping, and it appeared that the line had exploded internally. About 10 inches of line was missing; ends were burned, and exterior braid was folded back.

The consoles located to the west side had been blown partially over and had suffered rather extensive damage although there had not been much fire. However, the glass covers on pressure gauges were not broken. The roof panel over the console had been blown down onto the console.

There was much debris from the vehicle on the deck and piled on top of the engines, which at first glance gave the impression that this level was in shambles. However, structural damage was slight, and fire damage was that which would be expected from a rather hot, short-duration exposure, which charred flammables but did not heat metal unduly (FIG 7).

Level No. 5

Inspection of this level suggested that the explosion centered on this level, probably a few feet above the deck and near the west side of the vehicle. There was a considerable amount of structural damage above the deck. Safety railings were torn-off and thrown away. Horizontal wide flange I beams were bent horizontally, and some were torn loose. These beams had been located 10-20 feet above the deck, and deformations ranged up to about 2 feet in a 20-foot length (FIG 8).

Vertical columns were also deformed, although to a much lesser extent because they were of heavier section.

The air-conditioned instrument room at the west side was demolished by what appeared to be an internal explosion. The vertical power cable duct was badly deformed and broken open, and cable insulation was charred badly. The elevator shaft grille was blown in, lights were broken, and conduits were broken off their supports. There were no lightweight gutters left. Instrumentation cabinets on the east were severely burned on the outside, had opened, and suffered some internal fire damage.

There was much debris from the vehicle on this deck also, and some of the decking had been weakened. Many of the treads on the stairs leading to level 6 were bowed upward, and some were partially cut by fragments.

Level No. 6

Structural members at the deck level and above appeared to be undeformed except for one light horizontal beam at the north end. The northwest hinged floor grating was wedged into a partially raised position by debris, while the northeast one was supported in a raised position by interference with a railing plate. Some of the guard rails were bent. The door to the room at the west side had been blown open, and the window opposite the door was blown out; however, there appeared

to be little damage to the walls. The latter appeared to be 1/4-inch steel and to have deformed perhaps one inch in 4-foot spans. No fire damage was apparent within the room even though papers were exposed.

Level No. 7 and Above

The shed on top of the elevator, which was covered with corrugated sheet iron, had suffered some blast damage; the sheet metal was bent and was rolled-up or torn loose in places. The vertical cable duct was deformed and blown open (FIG 9).

There appeared to be no other damage of consequence except that the glass windows in the crane cab were broken.

SIGNIFICANCE OF FINDINGS WITH RESPECT TO MAGNITUDE OF EXPLOSION

Several different estimates of equivalent explosive weight were obtained by considering damage to specific structures. It is noted that the particular structures selected for analyses are of widely different types, responding to varying conditions of load-time histories, and that the estimates of yield required to produce the damages obtained may consequently vary considerably. At the farther distances, an overpressure criterion may more nearly represent the criterion of failure. At the intermediate distances, damage becomes more a function of a combination of overpressure and positive impulse; while at the very close-in distances, an impulse criterion may be assumed to govern. In arriving at the following estimates of yield, these criteria have been assumed and judgments have been made from experience gained in correlating the damages from this accident with those on similar structures from known explosive quantities.

Estimate of Explosive Weight Based on Damage to TS-1 Butler Building

This building was a lightweight sheet metal structure measuring 20' x 48' x 15'. It was positioned end-on to the direction of blast with the nearest end surface at a distance of 210 feet from a point on the ground directly below the assumed center of detonation.

Damage sustained by the Butler building was considered to be relatively light. The most extensive damage occurred on the end facing the blast, which would have been within the Mach stem. A general description of the damage would include a wrinkling to a slight crushing of the corrugated steel panels of from four to six inches in both the side walls and roof. Several windows were broken on the sides receiving the more direct blast, but only one was broken on either of the other two sides. Several structural members in the roof were slightly buckled or deflected a maximum of two inches while several others were loosened at the joints.

It has been assumed that a reflected overpressure of nearly five psi would be necessary at the near end of the building to produce damage of this extent from a relatively short (something less that 50 milliseconds) duration blast wave. The side-on overpressure at the near end of the building would then be approximately 2.5 psi and would require a high explosive weight of approximately 760 pounds.

Estimate of Explosive Weight Based on Damage to Cover Protective Assembly

The Cover Protective Assembly was a truncated conelike structure (FIG 10) fabricated from aluminum, estimated to be approximately 1/16 inch thick. Its base diameter was 12 feet, and it tapered to a top-opening diameter of four feet. In all, there were 12 panels fastened to longitudinal stiffeners. The height of the structure was approximately six feet. The cover was positioned face down with its center 125 feet from a point on the ground beneath the explosion center. Permanent inward crushing, to a depth of six inches, was observed in several of the panels facing the blast.

The estimate of explosive weight required to produce such damage was made by using damage threshold curves similar to those given in BRL Memorandum Report 1461 but revised to include recent data. For analysis, the cover assembly was treated as a right circular cylinder with the following characteristics: length, 6 feet; diameter, 12 feet; skin thickness, 0.062 inch; material, aluminum. It was further assumed that the stiffeners increased by 10 percent the overpressure required for crushing. The analysis shows that an explosive charge of TNT weighing 1,200 pounds would be required to produce approximately the same degree of damage. The analysis also includes the assumption that the structure would have been in the Mach stem portion of the blast wave.

Estimate of Explosive Weight Based on Damage to I-Beams

The beam chosen for analysis (FIG 11) was the horizontal structural member (8WF 17 I-Beam, 25 feet long), located on the north side of the test stand at level 5. All the horizontal members at this level were damaged, as were some at the next higher level, 10 feet above. This beam was selected for analysis since its permanent deflection was appreciably more than allowable in the elastic range without excessive buckling. The beams on the west side were sheared from the vertical member and severely distorted and buckled. The permanent deformation of the horizontal beam on the east side was considered to be too nearly the maximum allowable elastic deflection and, to some extent, was shielded by the tank from the explosion center.

To arrive to an effective weight based on beam damage, an analysis based on work by Norris, et al., of the Massachusetts Institute of Technology (Ref. 2) was employed. The method involves transforming the

actual beam system into an idealized mass-on-spring, single-degree of freedom system. Certain transformation factors are applied, and the system is analyzed in the plastic range.

To perform the analysis, certain assumptions concerning the loading had to be made. For simplicity, the beam was considered to be simply supported and uniformly loaded. In actuality, the beam was fixed to the vertical columns and was probably not loaded uniformly since one end was several feet closer to the apparent center of explosion than the other. It was also assumed that the loading was impulsive with a positive duration approximately 1/20 the natural period of the beam. The beam was considered loaded in the strong direction; however, observations showed that some loading also occurred in the weak direction.

Based on the permanent deflection of approximately 12 inches at the center of the beam and a distance of 13 feet from the center of explosion to the beam center, it is estimated that a high explosive weight of 1,000 pounds would be required to produce such damage. This is believed to be an upper bound on the explosive weight needed to produce such a deformation based on this analysis. It is to be noted that deformation is based on the magnitude of impulse associated with 1,000 pounds of high explosive and that the characteristic pressure-time history of the fuel explosion and high explosive at this distance may be quite different

Estimate of Explosive Weight Based on Glass Damage

Before attempting to judge the size of the explosion from the glass breakage, difficulties inherent in this method of estimation should be pointed out.

The first cause for concern is that the range of pressures required to break windows is reliably reported to range from 0.1 to 2.0 psi, depending upon the size, thickness, and mounting of the glass. The damage done to the windows of the large double trailer at the test site is a perfect case in point. There were three identical windows on the side facing the explosion. Each had two panes, one fixed and one horizontally sliding. In each case, the fixed glass was broken. Thus, at first glance one might conclude that the trailer was at the exact "average" distance for glass breakage since exactly half the panes were broken. However, closer inspection showed that the fixed panes were held in their aluminum frames by plastic strips and glue, whereas the movable panes were set in rubber. In other words, the fixed panes broke because they were inherently more susceptible to breakage.

The second reason for caution in using this method of assessing blast yield is that correlations for glass breakage take the form:

$$d = KW^{1/3}$$

Here, d is the average distance for glass breakage; W the weight of explosive, and K is a constant. Thus, an estimate of W from d involves $(d/K)^3$, so the result is extremely sensitive to the poorly defined parameter d.

Subject to the foregoing reservations, it is possible to get an estimate of the yield. Inspection of all available data indicated that the analysis probably should be restricted to evidence from only two sites of glass breakage.

a. All the window panes facing the center of the blast were broken in the guard house, 540 feet from the explosion.

b. Of the 18 panes in the pump house that were roughly in line-of-sight, six were broken, 700 feet from the explosion.

At both locations, the panes were of the same thickness and were similar in size; some of them were glazed in a similar fashion.

These data indicate that the average distance for glass breakage, i.e., the distance at which about half the glass would have been broken, was between 540 and 700 feet. An appropriate formula to use is as follows:

$$d_{avg}(\text{feet}) = 55W^{1/3}(\text{pounds})$$

Using a value of 620 feet for d, which corresponds to a point located halfway between the two structures, W is estimated to be about 1,400 pounds. This corresponds to a side-on pressure of about 0.7 psi at 620 feet, which is within the expected range.

Estimate of Explosive Weight Based on Fragment Dispersion

Fragment dispersion data can be used to obtain an estimate of equivalent weight of explosive if information is available for the distance traveled, cross sectional area, weight, and drag coefficient of individual fragments, and also for the velocity and direction of the prevailing winds at the time of the explosion. For the S-IV All Systems Vehicle explosion, selected fragments were weighed and measured. Drag coefficients were estimated based on the following assumptions:

a. Plates were considered to be rectangular in shape, relatively thin, and substantially flat. The flight attitude was taken to be normal to the trajectory for 2/3 of the distance. These assumptions led to the following:

$$C_{D\ \text{assumed}} = 2/3\ C_{D\ \text{normal}}$$

$$A_{\text{assumed}} = A_{\text{normal}}$$

b. Cylinders were considered to be solid and to tumble so that 1/2 of flight was in normal and 1/2 in axial attitude. These assumptions led to the following:

$$C_{D\ \text{assumed}} = \frac{C_{D\ \text{axial}} + C_{D\ \text{normal}}}{2}$$

$$A_{\text{assumed}} = \frac{A_{\text{axial}} + A_{\text{normal}}}{2}$$

c. Rectangular blocks were approximated by cubes which were assumed to tumble in flight. These assumptions led to the following:

$$C_{D\ \text{assumed}} = 1.1\ C_{D\ \text{normal}}$$

$$A_{\text{assumed}} = 1.5\ A_{\text{normal}}$$

Extremely limited information indicated that, at the time of the explosion, the wind at ground level was from the southwest at roughly 8 to 12 knots. No information was available for altitudes greater than 100 feet.

Figures 12 and 13 indicate the relation between initial velocity and distance traveled for fragments of different drag coefficients, cross sectional areas, and weights using an assumed flight angle of 45°. Table IV gives the identities and pertinent data for selected fragments from the S-IV All Systems Vehicle explosion and initial velocities estimated from FIG 12 and 13.

To obtain an estimate of equivalent explosive weight, the initial velocities given in Table IV were compared with unpublished data for fragments resulting from explosions involving known weights of high explosive. For American 2,000-pound general purpose bombs containing approximately 1,100 pounds of high explosives, secondary structural fragments had initial velocities generally within ±20 percent of those calculated for selected S-IV All Systems Vehicle fragments having similar drag coefficients. For American 1,000-pound bombs containing 530 pounds of high explosives, secondary structural fragments had initial velocities appreciably lower (approximately 40 percent) than those for S-IV All Systems Vehicle fragments with similar drag coefficients. Therefore, a value of approximately 1,100 pounds of TNT is taken for comparison with the other estimates.

The lack of precise wind data and the necessity for assuming a 45° angle of flight greatly limit the value of estimates of equivalent explosive weights based on fragment dispersion patterns. The result of this analysis of selected fragments, therefore, is included only because it tends to confirm the estimates obtained by other methods.

Summary of Explosive Weight Estimates

The several estimates of explosive weight may be summarized as follows:

Basis	Estimated Weight Pounds
Damage to Butler Building	760
Damage to Cover Protective Assembly	1200
Damage to I-Beams on Test Stand	1000
Glass Breakage	1400
Fragment Dispersion	1100
Average	1090

The agreement between estimates derived by different investigators from analyses of diverse types of damage is surprisingly good (all values within ± 50 percent of the average value) and may be fortuitous. Based on the total weight of on-board propellants at the time of the explosion, the average TNT yield is about one percent by weight.

This relatively low yield (one percent) may be compared with the value of 60 percent currently used for siting of LOX/LH2 vehicles. Since only that portion of the propellants which is mixed at the time of ignition can contribute to the yield of an explosion, the influence of ignition delay time on the magnitude of explosive yields is marked. In general, it would be expected that the yield for any particular quantity of propellant and any mode of failure would increase from a very low value approaching zero for a zero delay time to a maximum value for a delay time of a few seconds and then gradually decrease because of loss of propellants by evaporation. This suggests that the substantially instantaneous ignition of the propellants discussed above was largely responsible for the relatively low explosive yield. Therefore, it is important to consider whether similarly short ignition delays, and consequently similarly low explosive yields, can be expected in future incidents. No definite conclusion to this effect is possible at this time. However, the generally low yields (less than 15 percent) experienced with failures of LOX/RP-1 vehicles suggest relatively poor mixing. Moreover, small scale spill tests involving LOX/LH_2 frequently have resulted in premature ignition because of static discharges or other causes. Also, tests in which burst diaphragms have failed due to overpressurization with hydrogen gas have resulted in ignition. Similar premature ignitions have not been experienced with LOX/RP-1. These factors, therefore, suggest that the extreme flammability of LH_2 may serve to reduce its explosive hazard by insuring minimum ignition delays. Unfortunately, the reduction in explosive yield may be accompanied by an increase in the frequency of explosions resulting from minor leaks or spills that would not become catastrophic if ignition did not occur.

SIGNIFICANCE OF FINDINGS WITH RESPECT TO SIZE AND DURATION OF FIREBALL

Figure 14 was reproduced from the film of the explosion taken with the downstream camera; arrows indicating the diameter of the fireball are included for reference. These data indicate that the fireball reached some 70 percent of its maximum diameter of 380 feet within about two seconds, engulfing the entire test stand. It appeared to begin to diminish in intensity after about eight seconds and had substantially subsided after 11 seconds, although some burning of combustible materials and of propellants leaking from open lines continued for approximately six hours. The water deluge system was rendered partly inoperative by the explosion and had little effect during the first few seconds.

Figure 15 shows the maximum diameter attained by the fireball with similar values derived from small scale experimental tests and full scale vehicle failures involving LOX/RP-1 and LOX/LH_2 and N_2O_4/Aerozine 50. The data are logarithmically related in accordance with the equation:

$$\text{Log } y = 0.992 + 0.320 \log x \qquad \text{(Eq. 1)}$$

y = maximum diameter of fireball, feet

x = weight of propellants, pounds

S_y = standard error of values of log y calculated with Eq. 1 = 0.122

σ_a = standard error of intercept of Eq. 1 = 0.036

σ_b = standard error of slope of Eq. 1 = 0.012

Although the individual values exhibit considerable scatter, this appears to be largely associated with the variability of results for different failure modes and delay times for a given propellant rather than being caused by plotting data for different propellants on a single graph. The slope of the line, 0.320, does not differ significantly from a value of 0.33. Thus, it appears that cube root scaling used for other explosive parameters probably is applicable to fireball sizes.

Figure 16 shows the duration of the fireball together with similar values for small scale experimental studies and full scale vehicle failures. These data scatter widely and, therefore, are compatible with equations having a wide range of slopes. For consistency with the results obtained from the other explosive parameters, a slope of 0.33 is used; this appears to adequately describe the data. No doubt, much of the observed scatter is due to the difficulty in judging when the fireball has subsided.

Inspection of the test stand and its immediate surroundings indicated surprisingly little damage due to fire. Moreover, wherever evidence of burning was noted, the extreme lack of uniformity and occurrence of spotted burning patterns suggested that the dispersion of large quantities of LOX by the explosion markedly influenced the extent of damage. More specifically, it appeared that charring of painted surfaces was in many instances confined to areas exposed to LOX. It was of interest to note some of the items on the various levels which were not appreciably affected by the fire. Thus, a nylon rope on level No. 3 showed only one small (1/8-inch diameter) singed area. Scraps of a rubberized fabric used as a rain shield for the upper levels were scattered about the test stand. Although it was subsequently found that this material was badly burned by a 30-second exposure to a 700°F environment, most of the scraps noted about the test stand exhibited only localized burning or scorching, which suggests that the damage was limited to those areas contacting LOX.

Information expected to be derived from the small scale test programs should permit an estimate of the temperature of a black body radiator approximately equivalent to the flame from a LOX/LH_2 explosion. Such an estimate coupled with the fireball duration will permit calculation of the heat flux to a capsule or other exposed object.

SIGNIFICANCE OF EXPLOSION WITH RESPECT TO PROBABILITY OF FUTURE INCIDENTS

Because of the extremely limited experience, it is possible to consider the significance of the S-IV All Systems Vehicle explosion with respect to the probability of future incidents for LOX/LH_2 vehicles.

The hazard involved in tests with battleship tankage would be expected to be far less than that for tests using flight weight hardware. This discussion, therefore, is limited to static tests and launches of Centaur and S-IV flight weight vehicles. Table V summarizes experience with these vehicles to April 20, 1964. Although it is sometimes argued that tanking operations are less hazardous than static firings or launches, it should be noted that the tanking operations occur earlier in the development when the vehicle may be considered less proven. Also, it must be emphasized that both the Centaur and the S-IV All Systems Vehicle explosions occurred before ignition.

On this basis, the two failures correspond to approximately four percent of the population. Tables given in the appendix of Lloyd and Lipow provide an upper confidence limit for the probability of future incidents of approximately 16 percent for a confidence coefficient of 0.99 or 10 percent for a confidence coefficient of 0.95. Therefore, it appears that, even if the probability of future incidents is decreased as a result of learning, a sufficient number of incidents can be expected to warrant careful attention to risks and trade-off considerations attendant to siting of test and launch operations.

BLAST GAUGES

While examination of the damage resulting from an incident of this type permits a rough estimate of the magnitude of the explosion, a much more quantitative estimate would be possible if blast gauges had been installed at the test site. Inasmuch as this lack of instrumentation resulted in loss of quantitative blast data which probably would cost in excess of one million dollars to duplicate in a controlled experiment, it is considered essential to take additional steps to insure that any future incidents are adequately instrumented.

CONCLUSIONS

The evidence obtained from the different parts of this investigation appears to support the following conclusions:

1. The damage resulting from the S-IV All Systems Vehicle explosion was relatively slight and may be characterized as follows:

Maximum fragment radius	1,500 feet
Maximum fireball diameter	380 feet
Fireball duration	11 seconds
Explosive yield	1 percent

2. The relatively low yield was due to substantially instantaneous ignition of the spilled propellants, which suggests that the extreme flammability of hydrogen may provide generally shorter ignition delays than those experienced with LOX/RP-1 for actual vehicle failures. If this trend can be substantiated, some reduction in the 60 percent TNT equivalent currently used for siting of LOX/LH_2 vehicles may be possible.

3. Unfortunately, the extreme flammability of hydrogen may tend to increase the frequency of incidents since small spills or leaks which would otherwise be of no consequence may undergo ignition and lead to catastrophic failure. The loss of two LOX/LH_2 vehicles out of 49 tanking and firing operations to-date tends to substantiate this possibility.

4. The failure to have blast gauges in place and in operation at the time of the S-IV All Systems Vehicle explosion resulted in loss of significant information regarding the explosive hazards of LOX/LH_2. Action to insure against similar loss of information in future incidents is mandatory. end

[Maraging Steel]

TABLE I

PROPELLANTS AND GASES ON BOARD
ALL SYSTEMS VEHICLE AT TIME OF EXPLOSION

LOX Indicated Weight	84,244 Lbs.
LH_2 Indicated Weight	16,954 Lbs.
LOX Tank Pressure	100 psia - (Approximate)
LH_2 Tank Pressure	41 psia
Cold He Bottle Pressure	800 psia
Cold He Bottle Temperature	Off Scale (to approx. 25°R)
Volume LOX Tank	1,263 Ft^3 (specification value)
Volume LH_2 Tank	4,197 Ft^3 (specification value)
Volume Cold He Sphere (3 required)	3.5 Ft each (specification value)

TABLE II

IDENTIFICATION OF FRAGMENTS SHOWN ON FIGURE 3

<u>Southwest - Quadrant</u>

A-1	216	Fuel Tank Wall
	217	LOX Fill Line Elbow or Fuel TK Outlet Elbow to Low Pressure Duct
	218	Forward or Aft Interstage Structure
	219	Forward or Aft Interstage Structure
	220	Fuel Tank Dome
	221	Fuel Tank Wall
	222	Common Bulkhead
	223	Fuel Tank Wall
	224	Common Bulkhead
A-2	225	Fuel Tank Wall
	226	LOX Tank Vent Outlet Elbow
	227	Forward or Aft Interstage Structure
	293	LOX Tank Vent Outlet Elbow
	229	Aft Interstage Structure
A-3	228	Aft Interstage Structure
	231	Tank Structure Common Bulkhead Joint
	233	Fuel Tank Fwd Dome & Wall Section
	274	P/N 1A22765-1004 VDA Electrical Assembly
	291	Fuel Tank Low Pressure Duct
	292	Vehicle Roll Ring Support Lug 38717 (8 or 6) 2 - 401
A-5	232	Fuel Tank Bulkhead Attach Pt. With Vacuum Port
A-6	230	Fuel Tank Wall
	290	Anti Vortex Screen
	261	Accel. & Mt. Blk. Accel. S/N EA03 & EA02
	294	Aft Interstage Structure
A-7	295	Chilldown Duct Around Vehicle
	234	Fuel Tank Structure
A-8		Lower Skirt Skim
	296	Fuel Tank Anti Vortex Screen
A-9	297	Fuel Chilldown Doughnut Around Vehicle
B-4	235	Fwd. Int/Stg. Bulkhead & T/M & CDR Antenna CDR Cable #410W10P1
B-8	300	Chilldown Duct 1A01734-A45-1
B-9	298	Aft Interstage Structure
C-2	289	Meter IU Substitute Panel
C-4	262	IU Substitute Panel Meter
C-5	239	Fuel Tank Structure
	237	Interstage Structure Fwd Fuel Tank
	273	Accel. & Mt. Blk. FA08 & EA09
C-7	236	Fuel Tank Skin
C-8	656	Hyd Tank Skin
C-10	659	Skirt Structure

TABLE II (Continued)

C-10	664	Common Bulkhead
D-3	239	Fuel Tank Structure
D-6	238	Fuel Tank Structure
E-1	260	Fuel Tank Structure Cold Helium Bottle Mount Area
	280	Fuel Tank Structure
E-2	275	SI - Substitute Name Plate
E-5	260	T/M Ant. SW P/N 2884053-505F
E-8	6-80A	Steel Stand Structure
E-9	6-68	Wires - YY 745A18
		YY 742A18
		YY 744A18
		YY 740A18
E-10	299	Fuel Tank Wall
F-2	278	Interstage Structure
F-3	242	Fuel Tank Pressurization Duct
F-4	244	Point Level Sensor & Temp. Probe - Fuel or LOX Tank
F-5	243	Fuel Tank Structure Cold Helium Bottle Mount
G-4	240	Fuel Tank Structure
J-6	241	Fuel Tank Structure

Northwest - Quadrant

A-1	5	T.V. Camera Lens Portion
	6	Vehicle Instr. Temp. Assy. With Probes Probably LH_2 Tank
	7	FWD Dome Found on Def. Plate
	8	Stand Sheet Metal
	9	Camera Lite
	10	Blower
	11	IU SI Substitute Panel Meter
	12	IU SI Substitute Panel Meter
	13	4th Level Dust Fill Room Door
	14	Blower & Motor
	15	Fuel Tank Pressurization Flange & Clamp
	24	Fwd Dome (Piece) Found on Deflector Plate
	25	Vehicle Instr. Temp. Assy. With 7861475-567P Temp. Probes
	41	Base IU SI Rack
	42	IU SI Substitute Control Console
	43	2-1 1/2 Forward Dome Fuel Vent Valves Ducting
B-3	44	4882757
B-1	45	Top Panel IU SI Substitute
	1	Probe 7869839-501
	2	Vehicle Wire & Plug
	3	Vehicle Temp. Probe 7861475-567P
	16	Door 4th Level Dust Free Room
	18	Wall -- Dust Free Room

TABLE II (Continued)

B-1	19	3871762-4
	20	LH_2 Tank
	21	P/N 1A36695-1
	22	Vehicle Elect. Connector
	23	Type T42K 3 x 2 Regulator Face
	34	GSE Cable Assembly
	35	Cable Assy. GSE Controls
	36	GSE Cable Assembly
A-3	29	1734 Chilldown Duct
	30	Common Bulkhead
B-2	7	1A76599
D-1	27	Stand Structure 4 x 10 Sheet Metal
F-1	28	Interface Purge Duct
D-3	4	Vehicle Instr. Temp. Tree Probably LH_2 Tank
C-3	39	T/M & CDR Antenna P/N 5883605-1-002E
A-4	31	Temp. Probe S/N 1340N
A-7	40	Fwd. Interstage Bulkhead (2' x 4')
D-5	37	Endevco Accel. 22150-S/N FA05 S/N EA04
D-6	38	Common Bulkhead 3 x 3
C-6	32	LH_2 Tank Wall (2' x 4')
D-7	26	Fwd Interstage 1 x 1
G-2	26	Plate
	41	Vehicle Panel With Weld Bead
H-1	62	Tank Skin
H-2	67	Tank Skin
I-3	63	LH_2 Tank Structure
H-3	29	Vehicle Body Panel
	211	Vehicle Panel
	65	Hat Section
	68	1A03734 - Vent Duct
G-4	216	LH_2 Structure Tank
F-5	221	Aft Interstage Skirt
H-5	619	Tank Skin
G-5	218	Aft Interstage Skirt (Outer Surface)
H-5	614	LH_2 Tank Structure
H-6	613	Thrust Struct Skirt
A-7	654	LH_2 Tank Structure
	651	Skirt Structure
B-7	638	Lower Skirt Skin
	237	LH_2 Tank Structure
	636	LH_2 Tank Structure
C-7	660	LH_2 Tank Structure
D-7	639	Wire
	635	Skirt Channel
	631	Skirt

TABLE II (Continued)

D-7	630	LH_2 Tank Structure
H-7	620	Skirt Structure
G-7	623	Common Bulkhead Flange
A-8	155	LH_2 Tank Temp. Probe & Support
	249	LH_2 Vent Line Section
	653	Common Bulkhead
B-8	252	LH_2 Tank Structure
	658	Bulkhead LOX
	657	LH_2 Tank Structure
	645	Skirt
	641	LH_2 Tank Skin
	640	LH_2 Tank Structure (Large)
C-8	161	Aft Skirt Outer Skin
	648	Tank Structure
D-8	162	Two (2) Pieces LH_2 Tank Structure
	166	LH_2 Tank Structure
	233	LH_2 Tank Structure
	234	LH_2 Tank Structure
E-8	228	Tank Structure
F-8	224	LH_2 Tank Structure
	229	LH_2 Tank Structure
G-8	626	LH_2 Tank Structure
	627	Tank Skin
	622	Skirt Structure
A-9	247	LH_2 Tank Structure
	244	Thrust Structure Skirt Member
	646	Skirt Structure
B-9	242	Tank Structure
E-9	665	Skirt Structure
A-10	663	Fwd Dome Structure
A-13	667	LH_2 Tank Structure
A-14	269	Common Bulkhead One Face and Honeycomb
B-15	670	Common Bulkhead
A-15	271	Aft Skirt Piece With Spacer Bolt
A-16	173	Aft Skirt Spacer Strip
B-16	674	LH_2 Tank Insul. Liner
A-17	622	Tank Skin
D-20	175	Strip - Common Bulkhead Skin
B-22	676	LH_2 Tank Skin
C-22	677	Common Bulkhead
E-30	178	Aft Interstage Skirt Section

TABLE II (Continued)

Northeast - Quadrant

A-1	P-1	LH_2 Side of Bulkhead
	P-9	Support for 1A01738--55 Duct 1BXXXXX Support
	P-10	LH_2 Fill Diffuser Into Tank With Bellows
A-3	VDA-1	Pipe Assy. With Wires
	VDA-2	Temp. Probe Assy. S/N 1751, S/N 1788, S/N 1747, S/N 1761 S/N 1762
A-4	GSE-1	Lamp Fixture
	P-16	5' x 5' Section LH_2 Tank Fin #1 #4 Fuel Low Press. Outlet
A-5	G-4	Stand Common Cover
	P-15	Part 4' x 3' Common Bulkhead
A-6	VDA-4	Ignition Firing Unit S/N 017
	VDA-6	Bracket Assy. A-176
	VDA-5	Ignition Firing Unit S/N 019
A-7	VDA-3	Ignition Firing Units 411A1 & 411A2
B-1	P-2	1A01734-4732 Duct
B-2	P-5	Diff. Door S/N 153
	P-12	Aft Section Structure With Clips 1A36530-1-2 each
B-3	P-7	7851806-503 F&D Valve S/N 11084-011-004
	P-11	Diff. Door S/N 174
	P-8	1A24862-1 Expansion Joint 1A01734-55 Duct
	VDA-9	Potentiometer Cover
	VDA-10	Accelerometer S/N 2958 (A352), S/N 2966 (A353)
B-4	P-20	LH_2 Tank Vortex Screen
B-6	GSE-6	Cable Tray
D-1	G-3	Instrumentation Wiring
	VDA-8	Bracket Assy. 1A22765-1003
D-2	P-14	Section Common Bulkhead with Pumping Port & T/A to Manifold
C-2	P-13	Vortex Screen for Fuel Tank
	GSE-2	Lighting Fixture
	P-4	1A34689 Shroud (Part of) 1A01734 Duct N/A
	P-3	1AX6289-A45-1 Shroud, 1A01734 Vent Fwd Retainer Ring
C-4	GSE-5	Part of Instrumentation Temp. Assy. with Probe LOX or LH_2 Tank
D-6	VDA-7	Extensometer

Southeast - Quadrant

A-1	2	Common Bulkhead
	3	Skin Retro Rocket

TABLE II (Continued)

A-1	4	Aft Skirt Skin
	5	Fwd - Pad P/N 3871762-401A
	6	LH_2 - Tank Skin
	7	Common Bulkhead
	8	Fuel Tank Skin
	50	LOX Tank Baffle (Piece)
	51	Common Bulkhead
	52	LOX Tank Internal
	49	Piece Eng. Duct
	74	Bulkhead Seam
	75	Common Bulkhead
B-1	48	Piece Bulkhead Seam
	47	Piece Common Bulkhead
	45	Piece Common Bulkhead
	46	Piece Support Structure, (Tube) LOX Tank Part No. XXXXXX3-403
	73	Common Bulkhead
	54	Cable Assy. 41CW222
	53	Lite Fixture Cover Ex Type
A-2	60	Fwd or Aft Skirt
	19	Fuel Tank Skin
	20	LH_2 Tank Insul.
	61	Common Bulkhead
	70	Common Bulkhead
	72	Aft Skirt
	71	Common Bulkhead
B-2	68	Fwd or Aft Skirt
	69	Elect. Fittings (Ex)
	9	Common Bulkhead
	10	Bulkhead
	11	Bulkhead
C-2	44	Explosion Proof Light Fixture (Stand)
A-3	62	LH_2 Tank Skin
	17	LH_2 Insulation
	18	Aft Skirt
B-3	67	Common Bulkhead
A-4	65	Common Bulkhead Seam
	63	Common Bulkhead
	59	Common Bulkhead Honey Comb
	15	Common Bulkhead
	16	Common Bulkhead
	14	LH_2 Tank Skin
	13	Common Bulkhead
B-4	10-4	T/S Structure Sheet Metal
	43	Piece Common Bulkhead
	64	Pot Type Xducer S/N 1455

TABLE II (Continued)

B-4	12	Fuel Tank Skin
	66	Common Bulkhead LH_2 - LOX Seam
A-5	57	Common Bulkhead
	4-1	Common Bulkhead
	21	LOX Tank Vent Sect. Aft Skirt
	58	Chilldown Vent
	41	7866357-1 (Spec. Cont. Dwg.)
A-6	56	Chilldown Vent at Turnbuckle Tie Down
	55	LH_2 - LOX Bulkhead Seam
B-6	42	Sensor & Mount DAC Part No. 7861475-567M S/N 1742
D-7	6-32	Common Bulkhead Flange 10" x 3"
D-8	6-43	Outer Vehicle Fill Line Elbow - 45° 4"
	6-48	Hyd. Tank Skin Outer 2' x 3'
G-2	6-10	T.S. Cover Rod & Canvas
	6-12	LOX Tank Skin 3" x 3"
G-4	6-17	Thrust Structure Skin 4" x 4"
	6-25	Power Supply Elect. Box P/N 7860719-509 41501
H-1	6-4	LOX Tank Skin

TABLE III

DATA FOR SELECTED FRAGMENTS

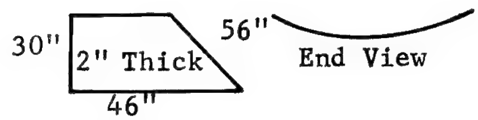
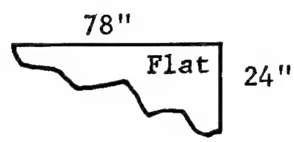
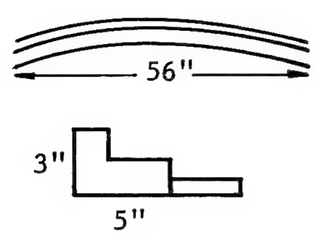
Item No.	Identification	Weight Lbs.	Distance Ft.	Size In.	Shape
1.	SW A-9 297	54	400	30 x 11	Cylindrical
2.	SW B-9 298	14	400		
3.	SW B-8 300	19	350	11 x 48	Cylindrical
4.	SW A-7 295	9	300	20 x 11	Squashed Cylinder
5.	SW A-7 234	5	325	18 x 8	Irregular Flat Plate
6.	4-56-6A	12	260	21 x 11	Squashed Cylinder
7.	A-5 SN4-1 Common Bulkhead	14	225		
8.	A-8 296	2	350	12 x 12	Flat Plate
9.	SW A-5 Fuel Tank Bulkhead	33	230		
10.	SW A-3 231	25	175	56	
11.	4-41-5B	2	220	30 x 6	Cylindrical

TABLE III (Continued)

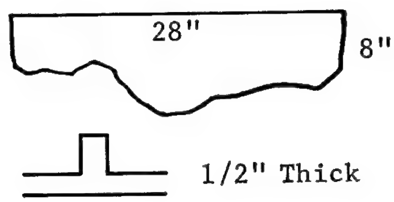
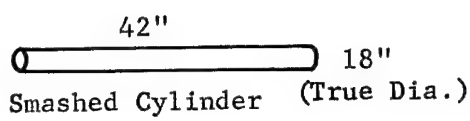
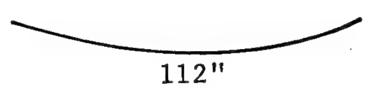
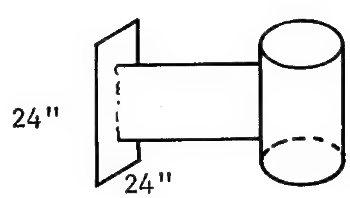
Item No.	Identification	Weight Lbs.	Distance Ft.	Size In.	Shape
12.	4-44-2C	11	110	10 Max. Diam.	Electrical Light Fixture Base
13.	1-B-4-48	1	60	1-3/4 ID	Cylindrical Tube
14.	P-14 3-+ 2+D	12	180		
15.	KRS #16 Common Bulkhead	4	50	24 x 10	Thin Plate 
16.	3-G2	10	120	10 x 7 ID	Electric Light Fixture
17.	P-12 3-+2++B Aft Section Structure	2-1/2	110	17 x 16 x 2	Flat
18.	P-6 3-+2+B	21	130		
19.	A-3 Common Bulkhead Tie-In To Skin	90	100		
20.	B-9	19	50		

TABLE III (Continued)

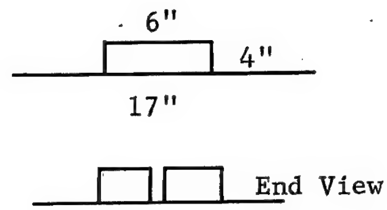
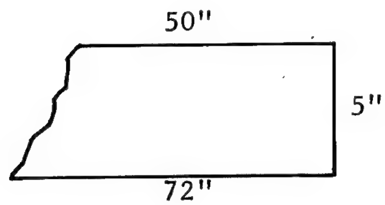
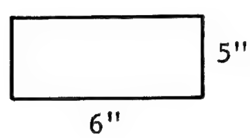
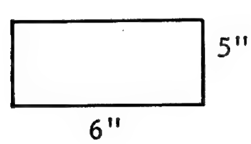
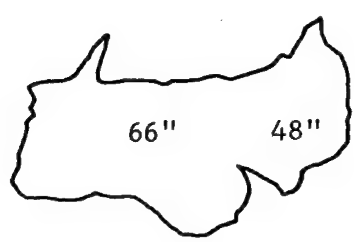
Item No.	Identification	Weight Lbs.	Distance Ft.	Size In.	Shape
21.	3B488 2757	13	?	8 x 3 Dia	Cylinder
22.	C-6 LH_2 Bulk-head, Flat Plate	24	300	2 x 4	
23.	A-7	10	350	2 x 4	Flat Plate
24.	VDA-3 Ignition Firing Units	9	350		
25.	P-16 Section of LH_2 Tank And Common Bulkhead at Outer Skin	85-90	?		
26.	A-6 Ignition Firing Unit	4	300		
27.	0-17 Ignition Firing Unit	4	300		
28.	KRS #12 LH_2 Skin Section Hit Fence While Burning Fence Not Dented	56	375		

TABLE III (Continued)

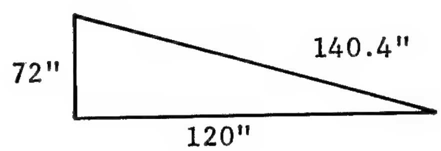
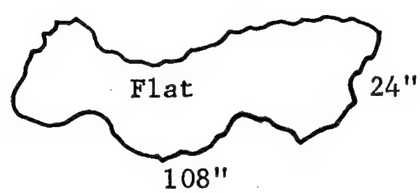
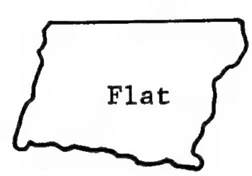
Item No.	Identification	Weight Lbs.	Distance Ft.	Size In.	Shape
29.	KRS-13 Fuel Tank Skin	26	375	48 x 36	Rectangular Curved 
30.	F-1 Interface Purge Duct (All One Piece)	150	225	24 Foot Long Cylinder (Diameter Not Measured)	
31.	100 Feet beyond the LH_2 Sphere are hundreds of pieces of glass.				
32.	7-B Major Size Part LH_2 Tank Structure	110	350	120 x 78	Flat Plate
33.	7-A LH_2 Tank	10	350	30 x 24	Flat Plate
34.	6-2-47 + A + 9	8	450	24 x 30	Flat Plate
35.	8-B LH_2 Tank (Burned)	100	450	 	
36.	6-41-8B	40	450	 	
37.	Grid 0-8 Area 6-48A LH_2 Tank	8	410	24 x 36	

TABLE III (Continued)

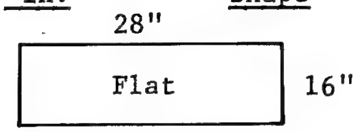
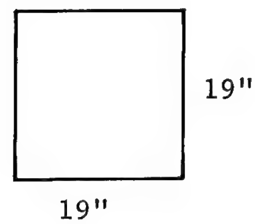
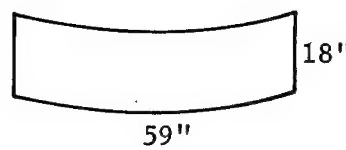
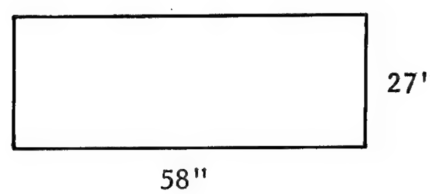
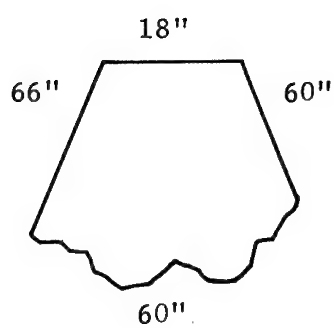
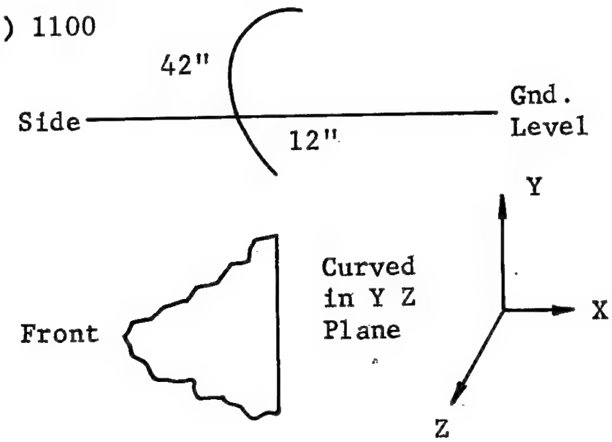
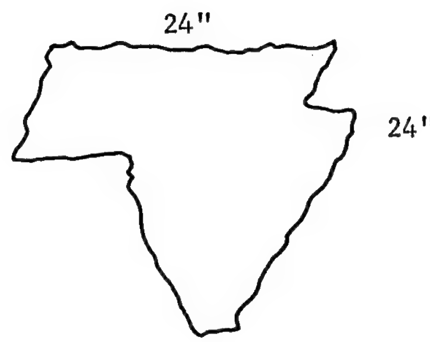
Item No.	Identification	Weight Lbs.	Distance Ft.	Size In.	Shape
38.	7-D 6-31	7	500		
39.	Grid 8-G Area 6 Part 22 4" buried in Ground on Edge	7	550		
40.	7-H Area 6, Part 20	26	550		
41.	6-2-21 Interstage Skirt + F + 5	28	350		
42.	10-A 363 LH_2 Tank Fwd. Dome Structure	30 Est	1100		

TABLE III (Continued)

Item No.	Identification	Weight Lbs.	Distance Ft.	Size In.	Shape
43.	6-67 13- -A LH_2 Tank Structure	20(Est)	1100		
44.	C-10 Area 6-59 Common Bulkhead	5(Est)	800		

NOTE: All weights over 80 pounds were estimated.

TABLE IV

CALCULATION OF INITIAL VELOCITIES FOR SELECTED FRAGMENTS

Item No.*	Weight lbs.	Assumed C_D	Area (Ft^2)	$\frac{C_D A}{W}$	Distance, Feet	Min. Vel. Feet/Sec.**
1	54	.77	1.48	.021	400	130
2	14	.79	.48	.027	400	137
3	19	.78	2.16	.089	350	180
4	9	.79	2.36	.207	300	450
10	25	.88	1.94	.068	175	95
14	12	.79	1.11	.073	180	95
25	87.5	.79	21.6	.195	300-350	530
26	4	1.6	.26	.104	300	165
27	4	1.6	.26	.104	300	165
39	7	.79	2.5	.282	550	> 4000
40	26	.79	7.37	.224	550	3000
41	28	.79	10.9	.308	350	1900

* Item numbers refer to Table III.

** Assumption of 45° flight angle gives velocities equal to or less than actual.

TABLE V

SUMMARY OF LOX/LH_2 EXPERIENCE
WITH FULL-SCALE FLIGHT WEIGHT TANKAGE*

	Flight and Static Firings	Tanking Operations
S-IV	5	6
Centaur	28	10

* Numbers are estimates based on results of informal inquiries to General Dynamics, Lewis Research Laboratory, and Marshall Space Flight Center personnel.

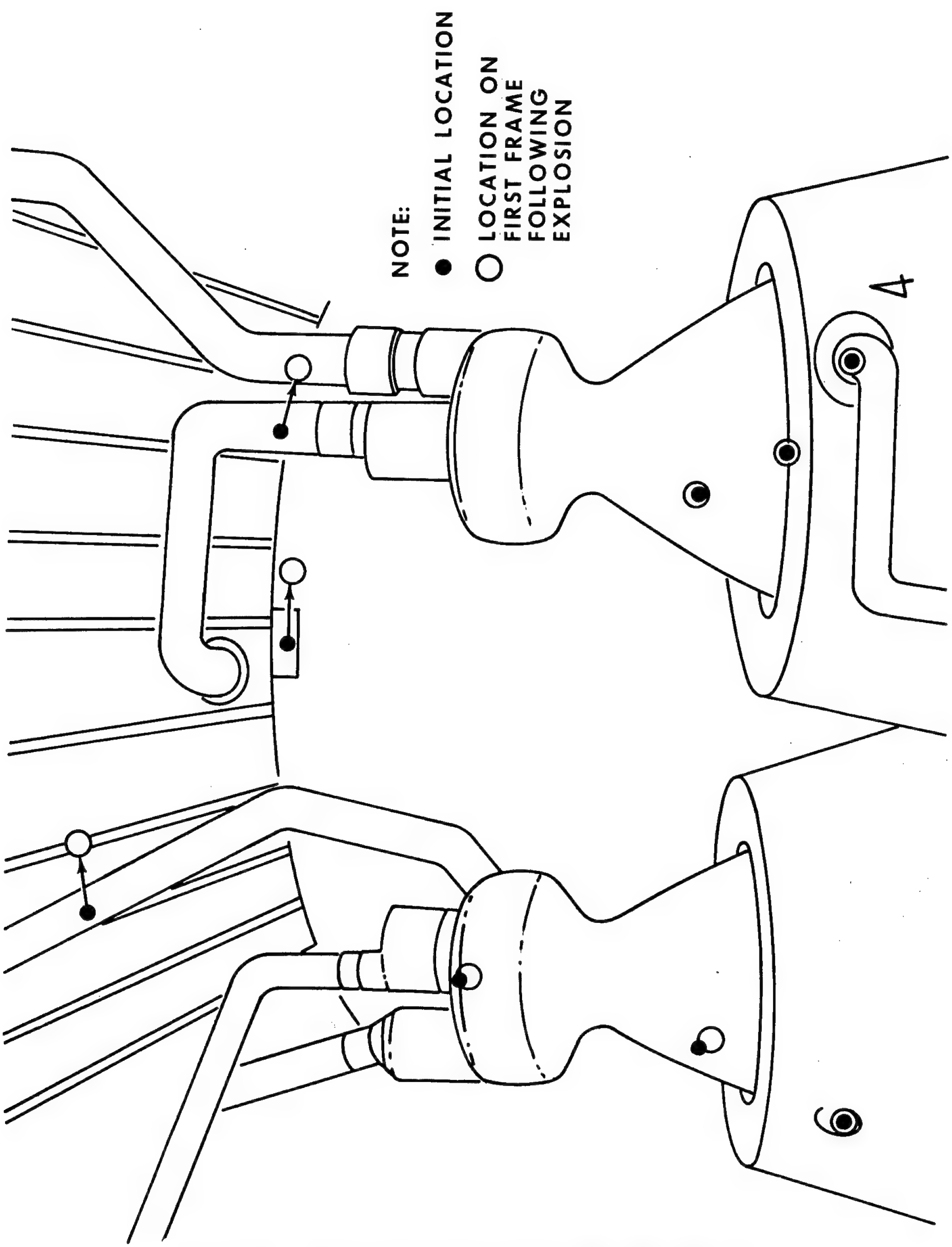


FIGURE 1. MOVEMENT OF VEHICLE AFTER EXPLOSION

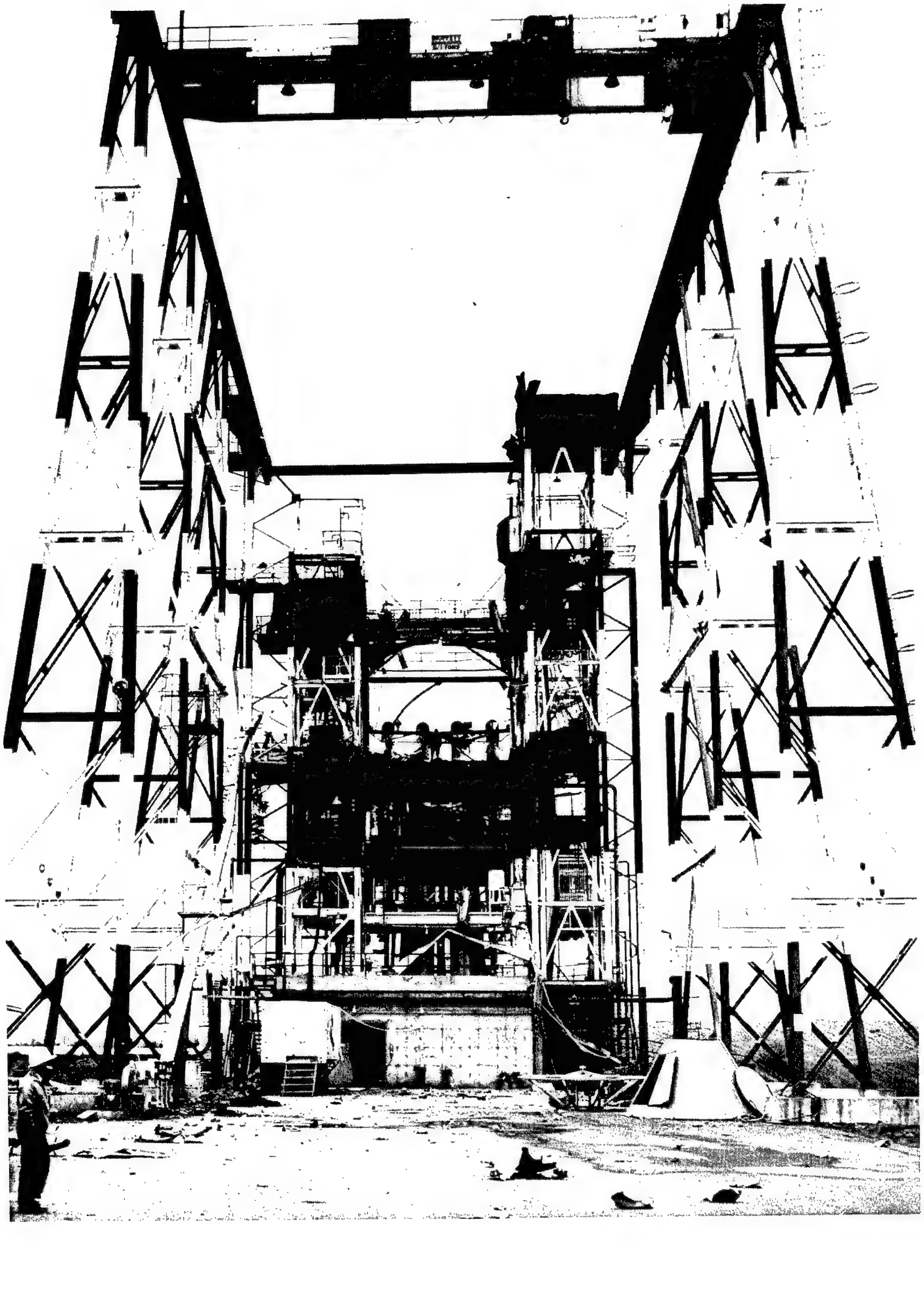


FIGURE 2. VIEW OF TEST STAND AFTER EXPLOSION

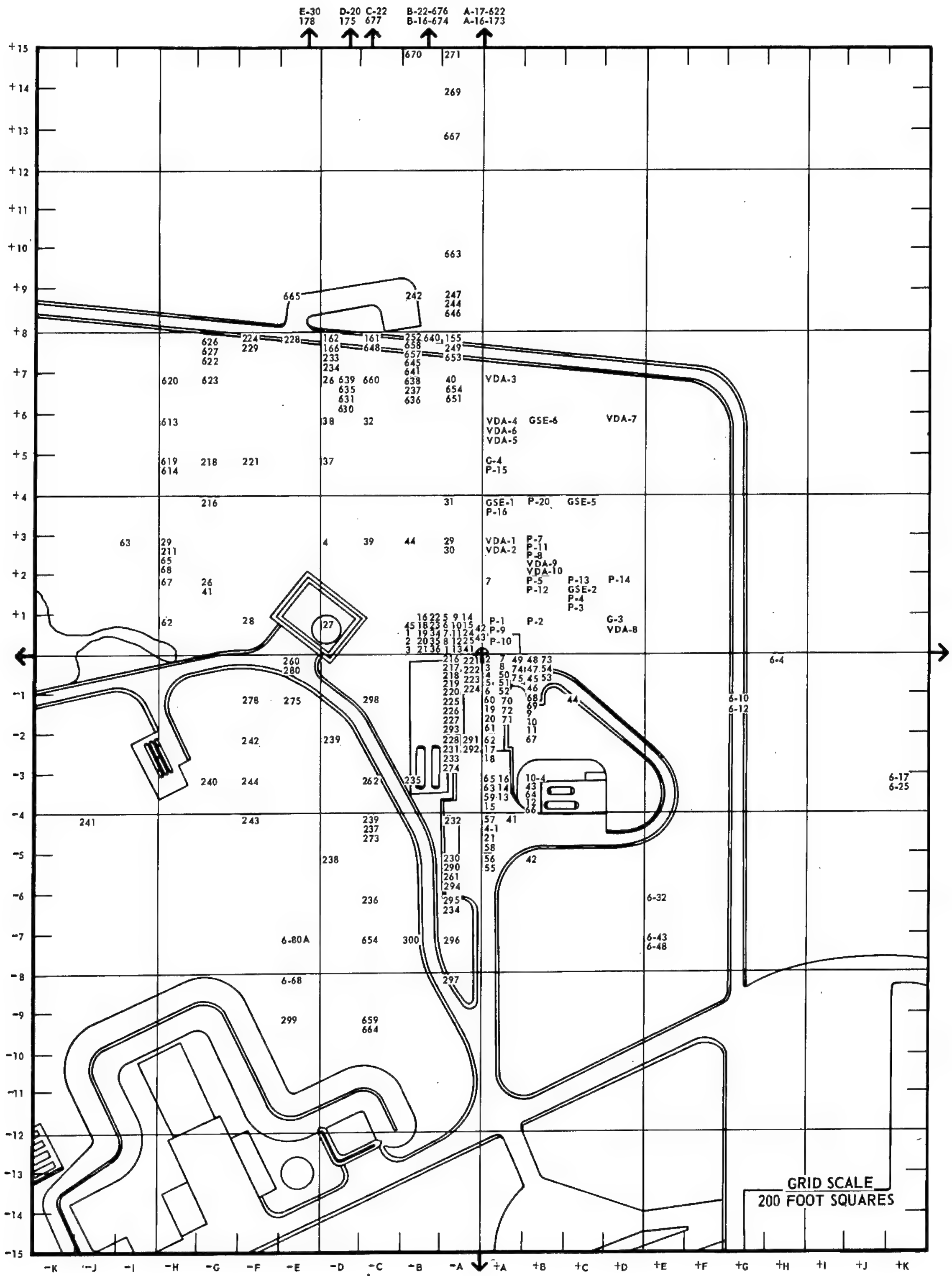


FIGURE 3. FRAGMENT DISPERSION PATTERN

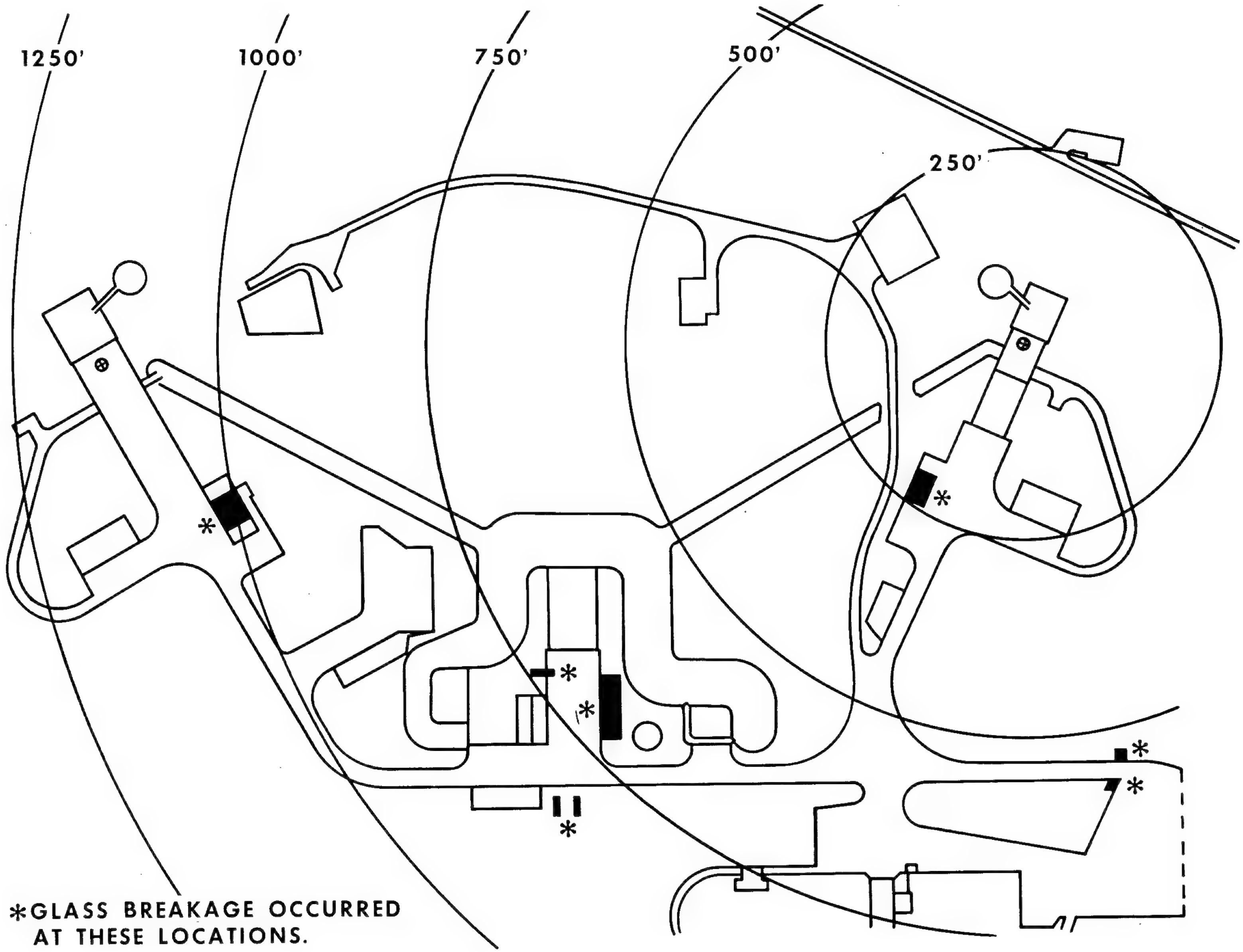


FIGURE 4. GLASS BREAKAGE PATTERN

FIGURE 5. DAMAGE TO BUTLER BUILDING, TS-1

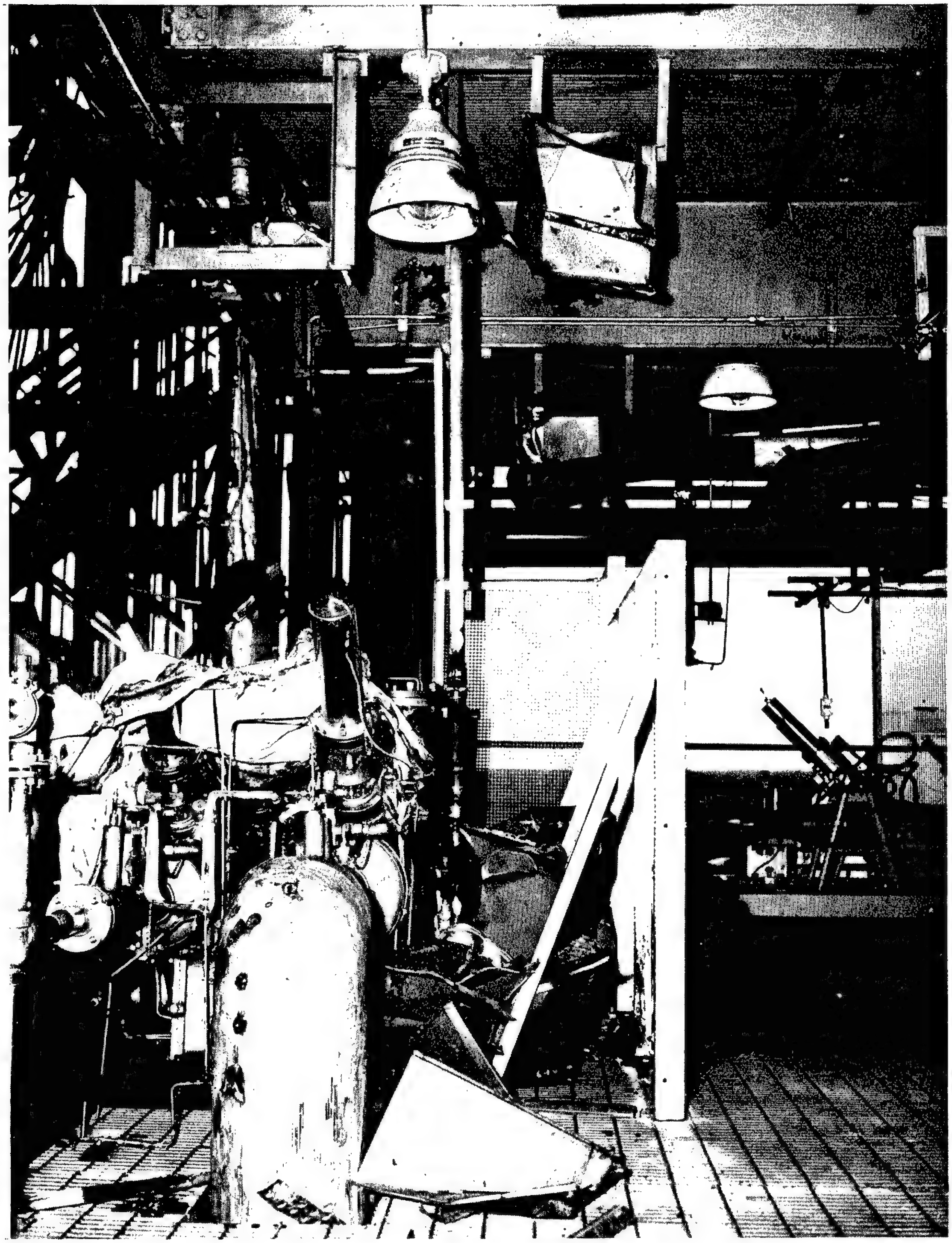


FIGURE 6. LIQUID HYDROGEN AND OXYGEN SLEDS (3rd LEVEL)

FIGURE 7. VEHICLE DEBRIS ON TOP OF ENGINES (4th LEVEL)

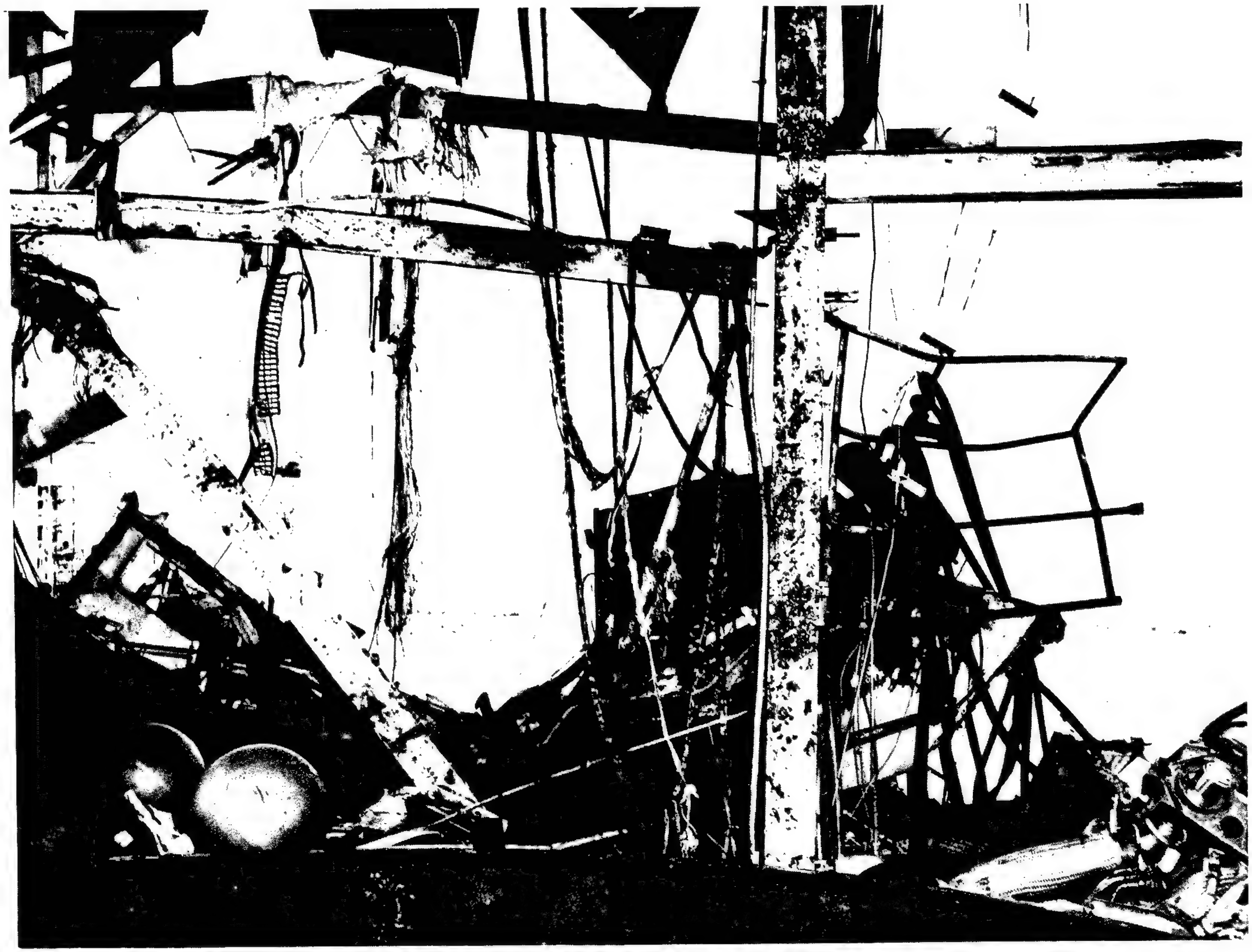


FIGURE 8. BENT STRUCTURAL MEMBERS (5th LEVEL)

FIGURE 9. CABLE RACEWAY AND ELEVATOR SHED (6th AND 7th LEVEL)

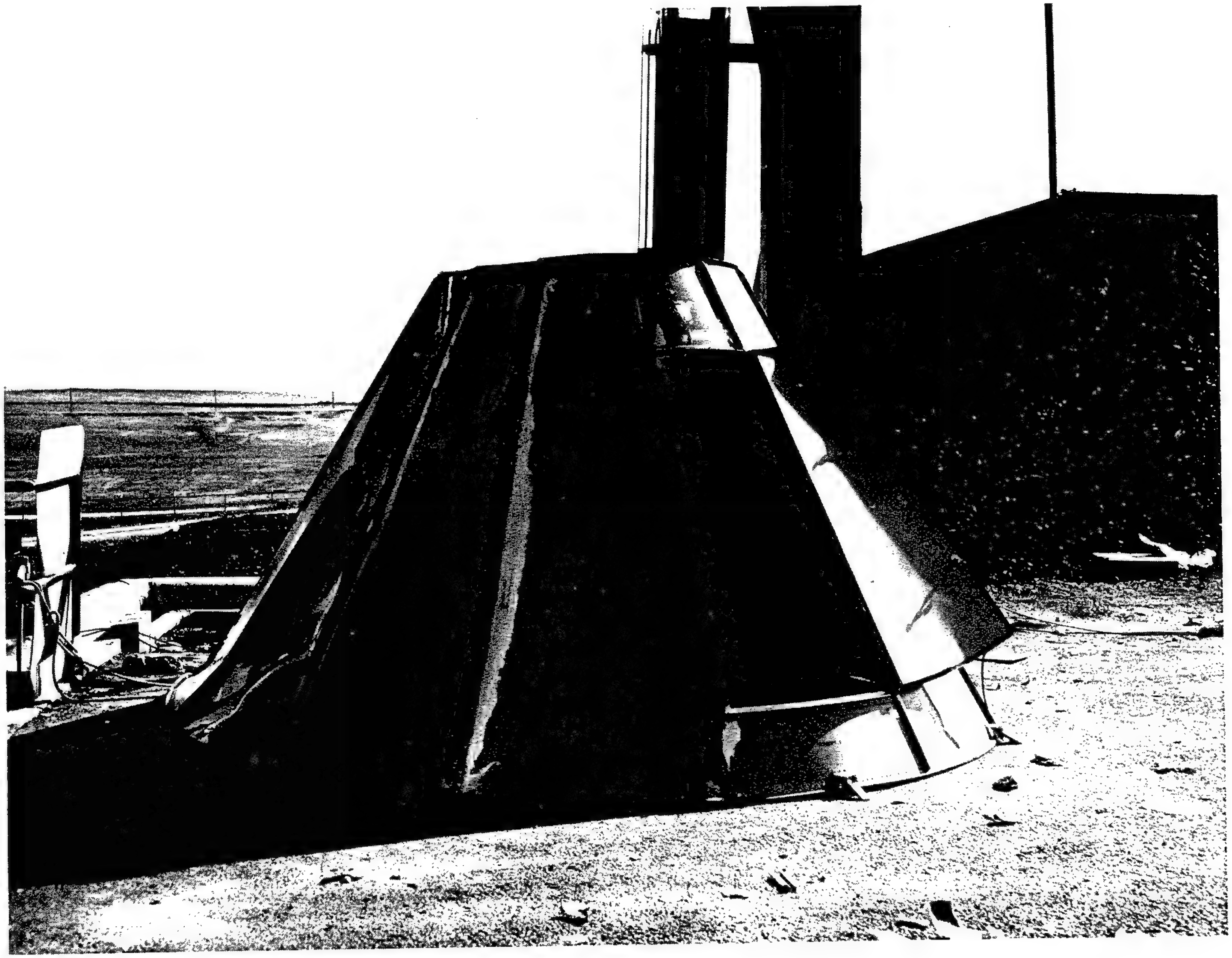


FIGURE 10. COVER PROTECTIVE ASSEMBLY

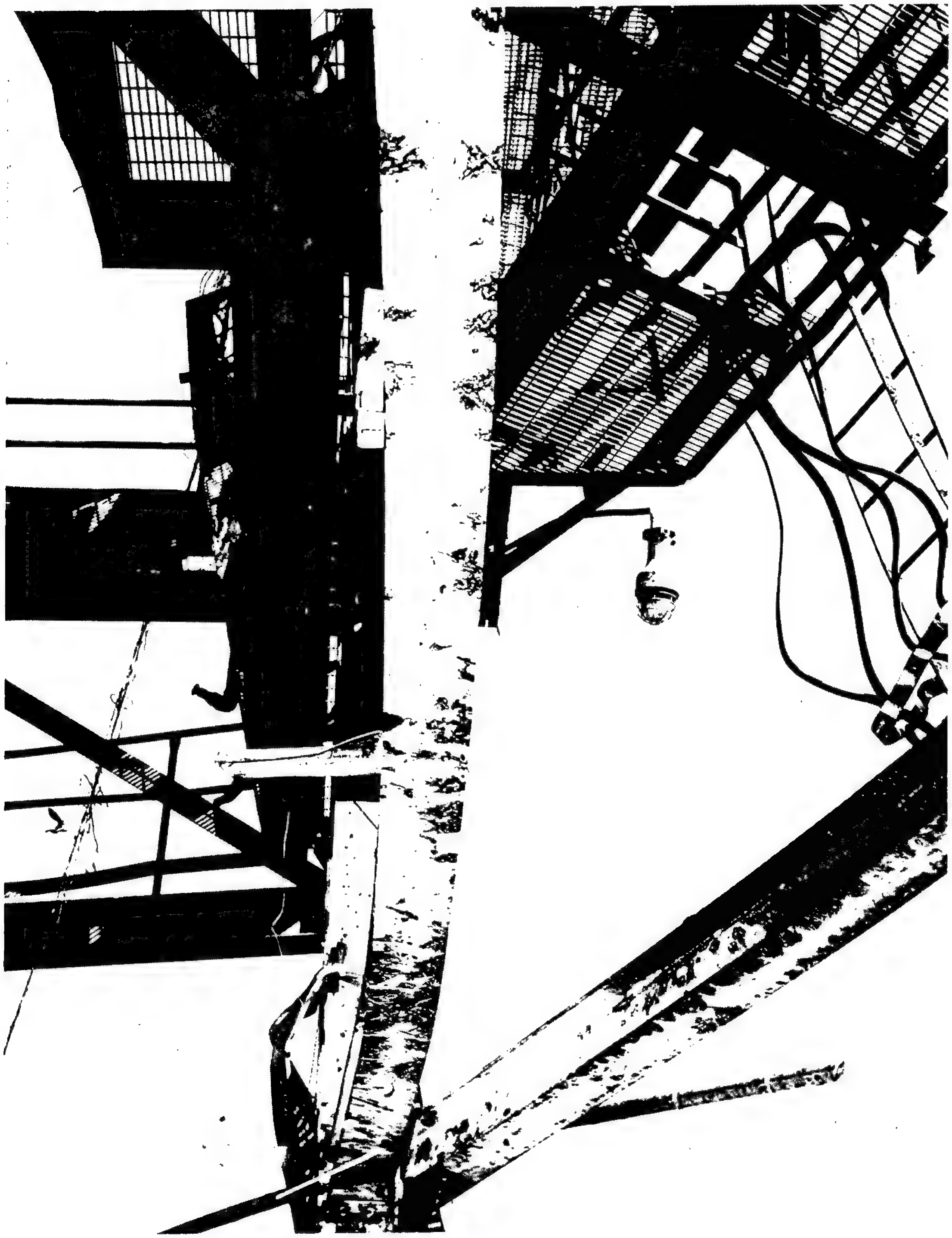


FIGURE 11. DAMAGED I-BEAM

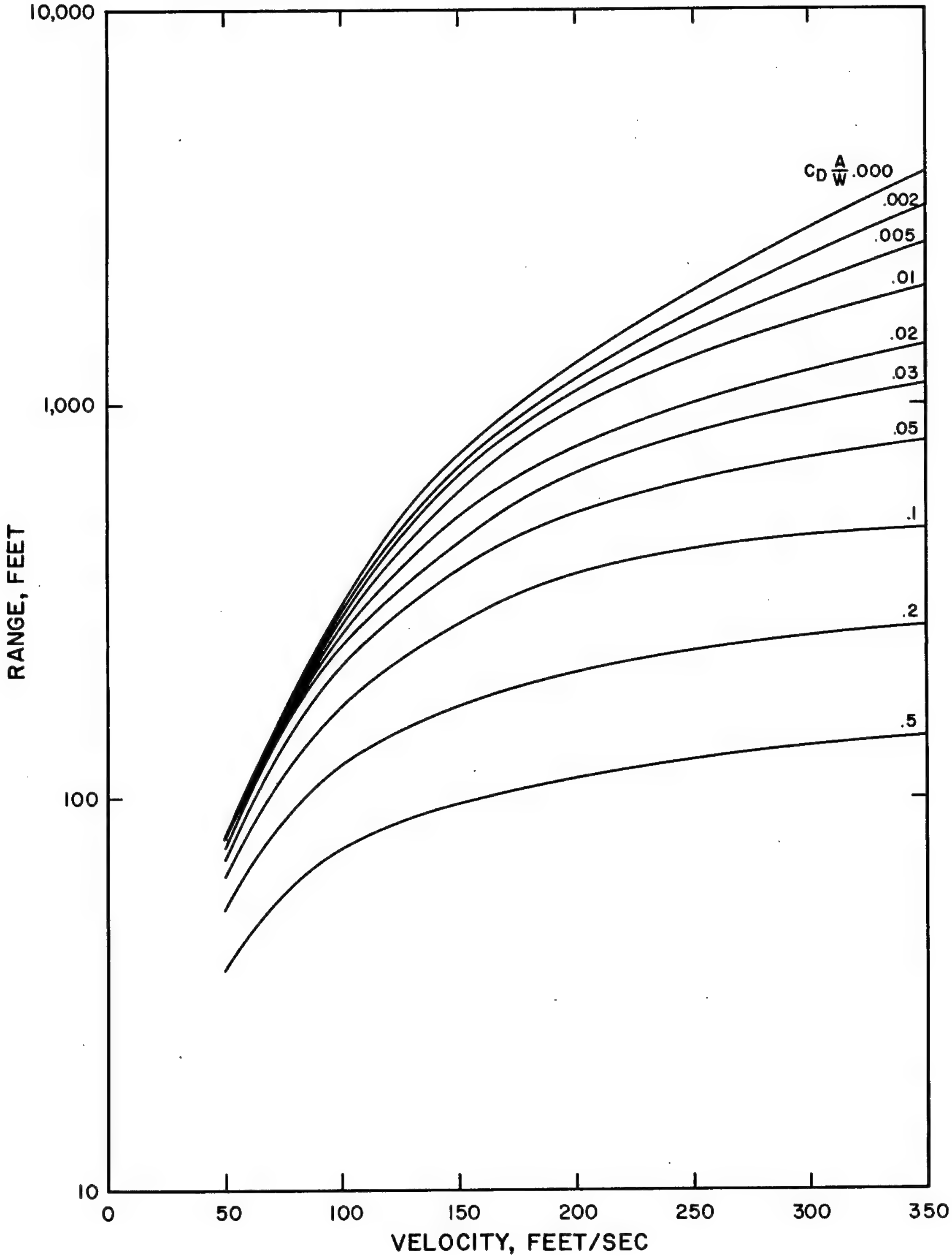


FIGURE 12. RELATION BETWEEN INITIAL VELOCITY AND GROUND RANGE (LOW VELOCITY RANGE)

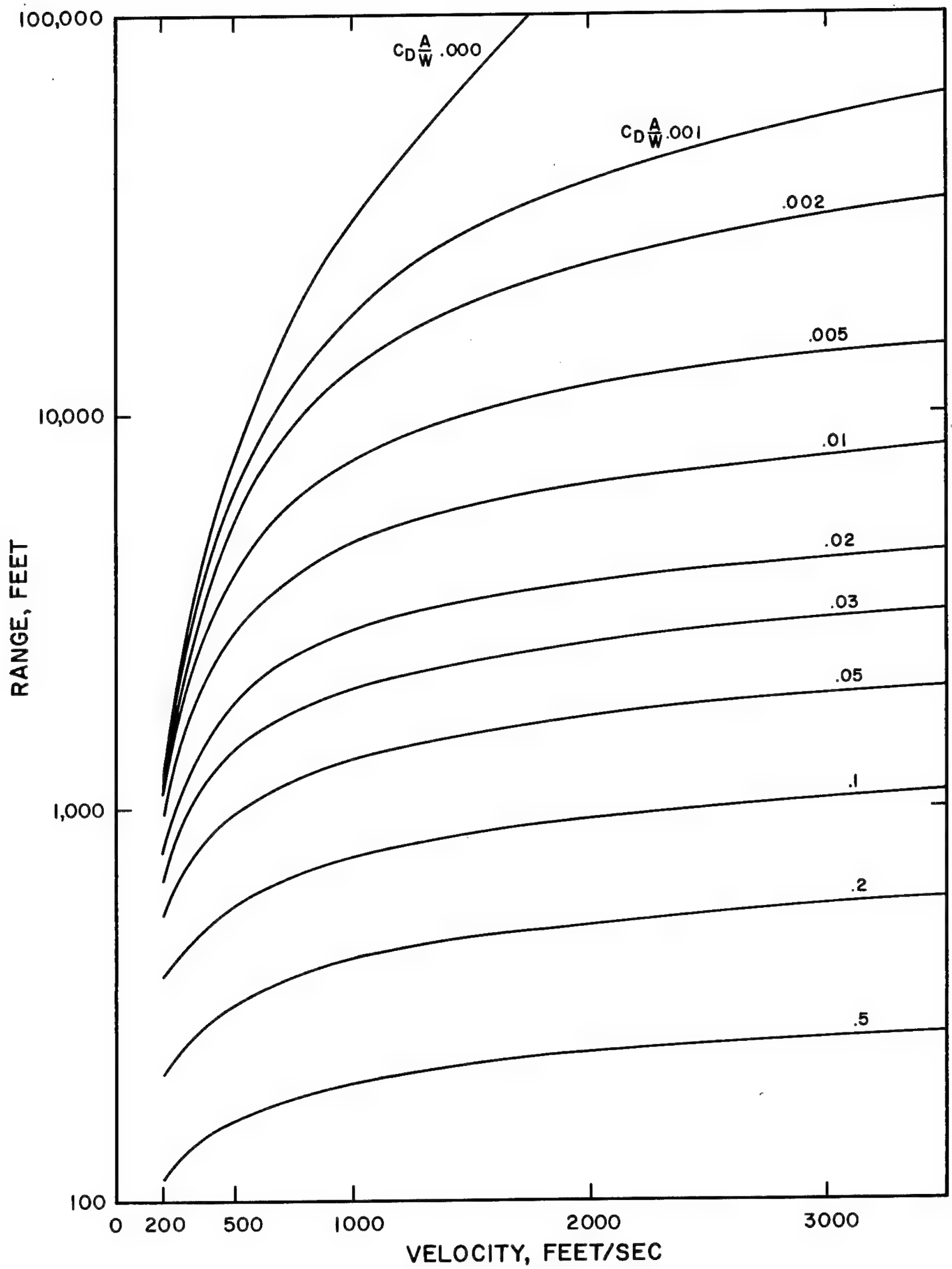


FIGURE 13. RELATION BETWEEN INITIAL VELOCITY AND GROUND RANGE (HIGH VELOCITY RANGE)

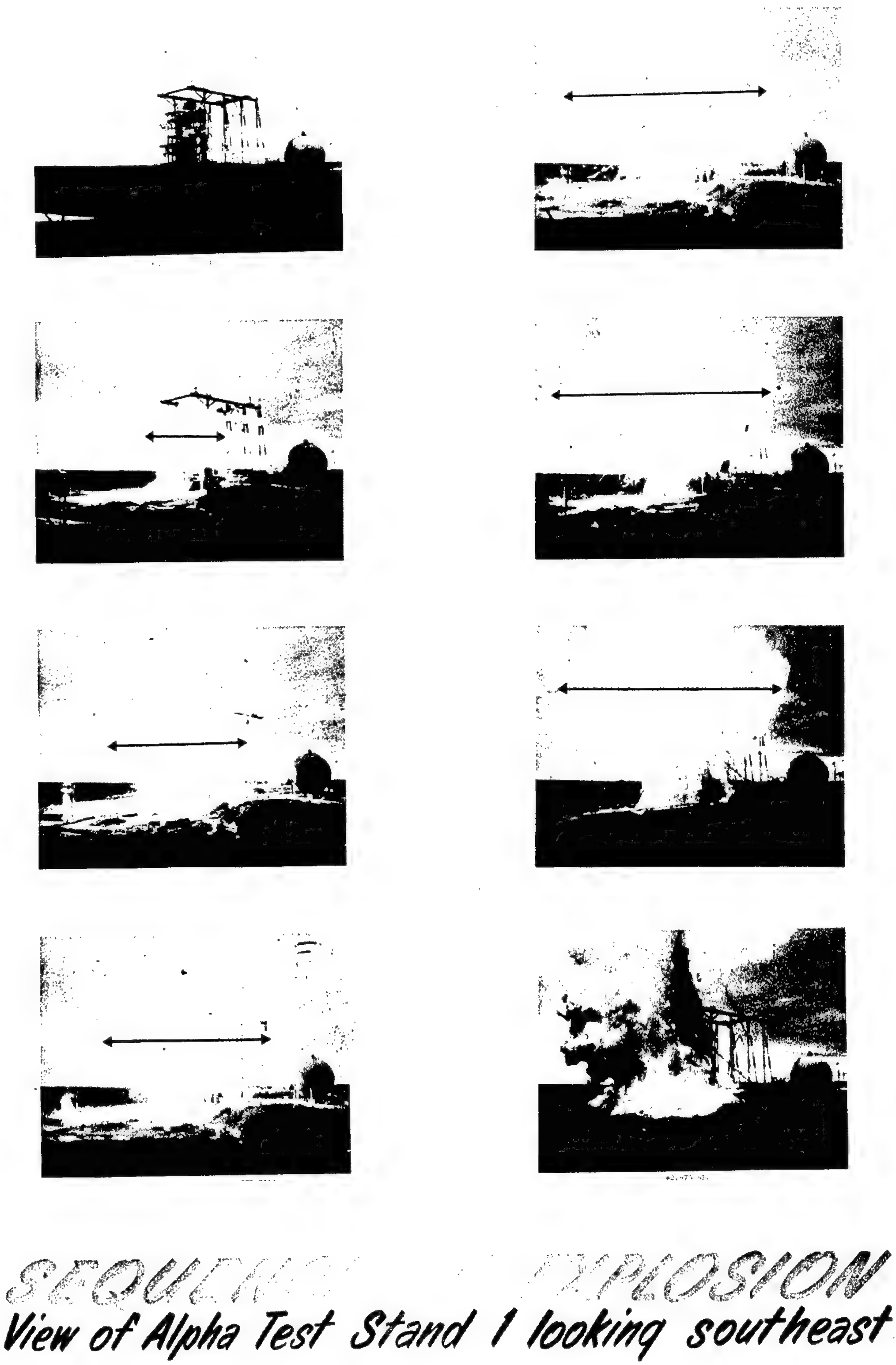


FIGURE 14. SEQUENCE OF EXPLOSION

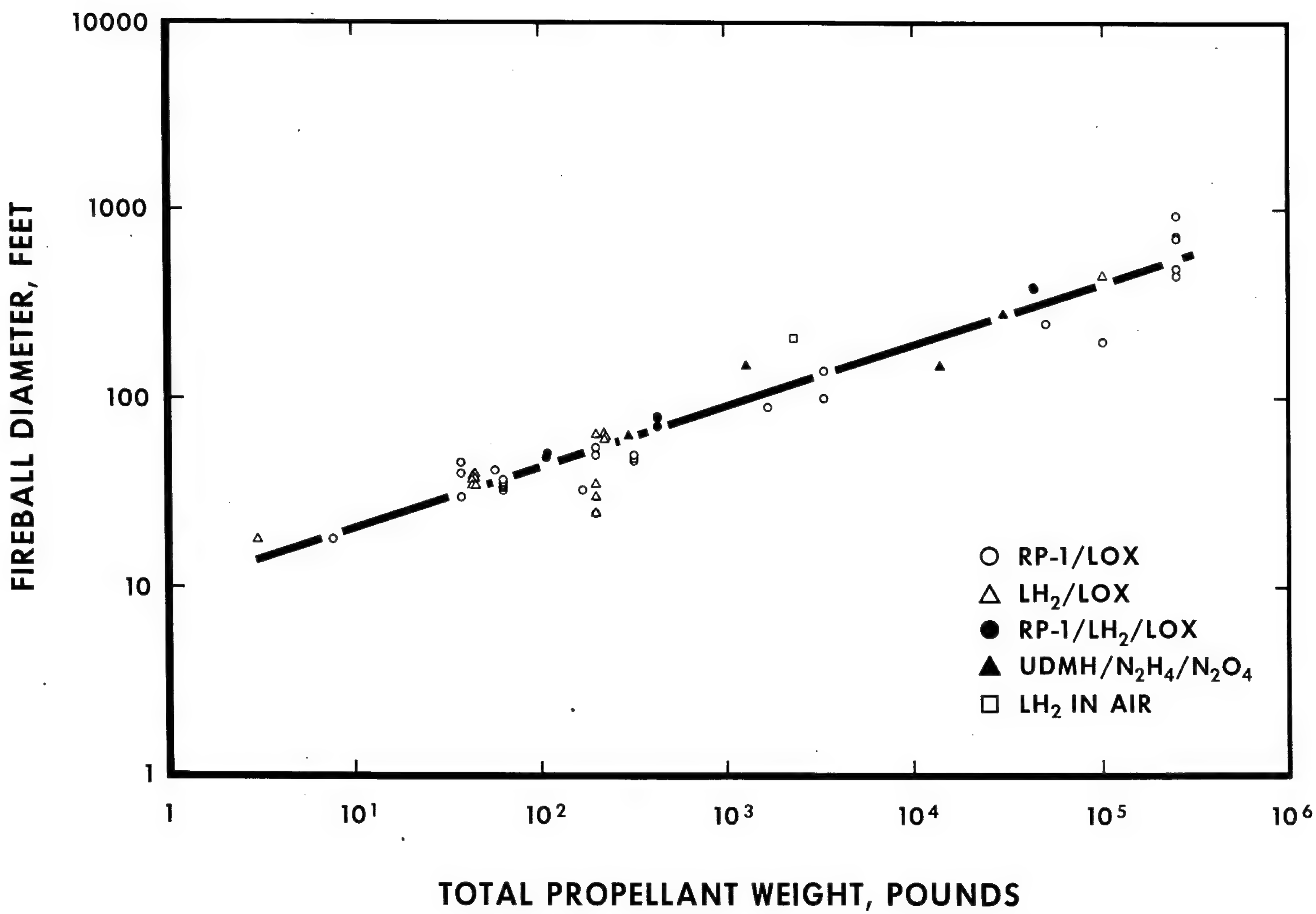


FIGURE 15. FIREBALL DIAMETERS FOR VARIOUS WEIGHTS AND TYPES OF PROPELLANTS

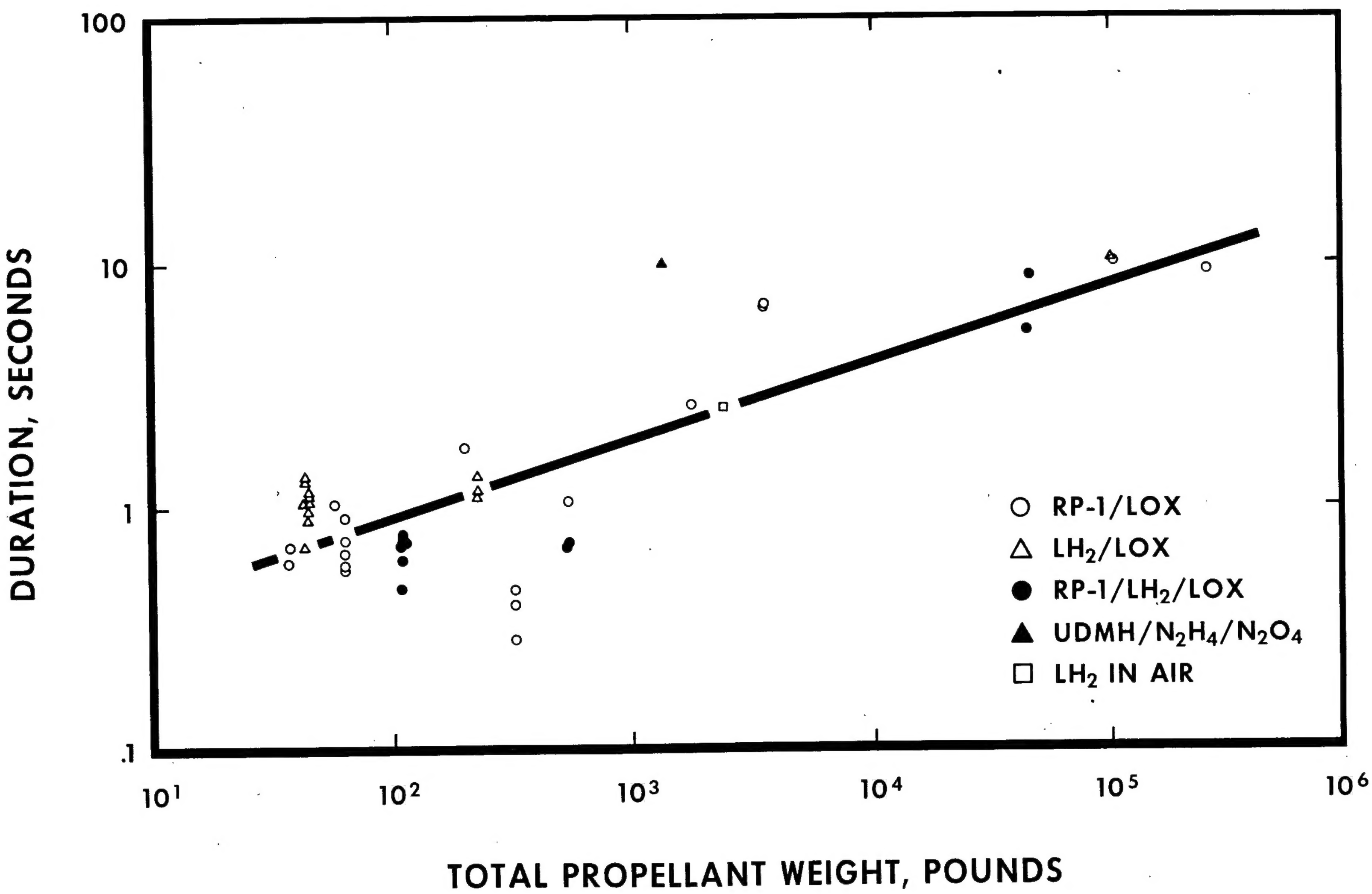


FIGURE 16. FIREBALL DURATION FOR VARIOUS WEIGHTS AND TYPES OF PROPELLANTS

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